Carbon Sequestration Rocks

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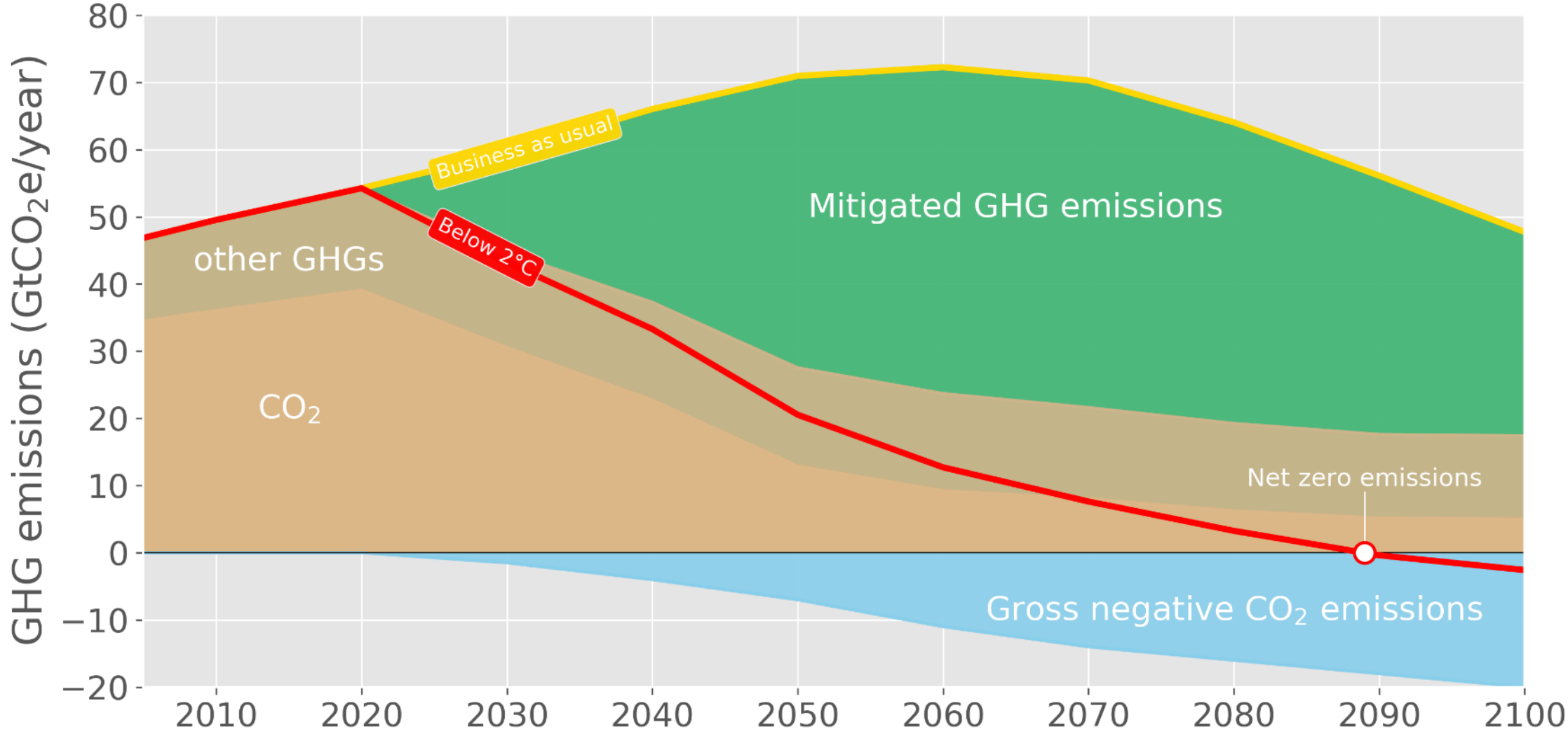
Negative emission technologies (NETs) are vital



Plot is homemade, but adapted from: National Academies of Sciences, Engineering, and Medicine. “Negative emissions technologies and reliable sequestration: a research agenda.” (2018); uses LIMITS Scenario database: https://tntcat.iiasa.ac.at/LIMITSDB/dsd?Action=htmlpage&page=welcome

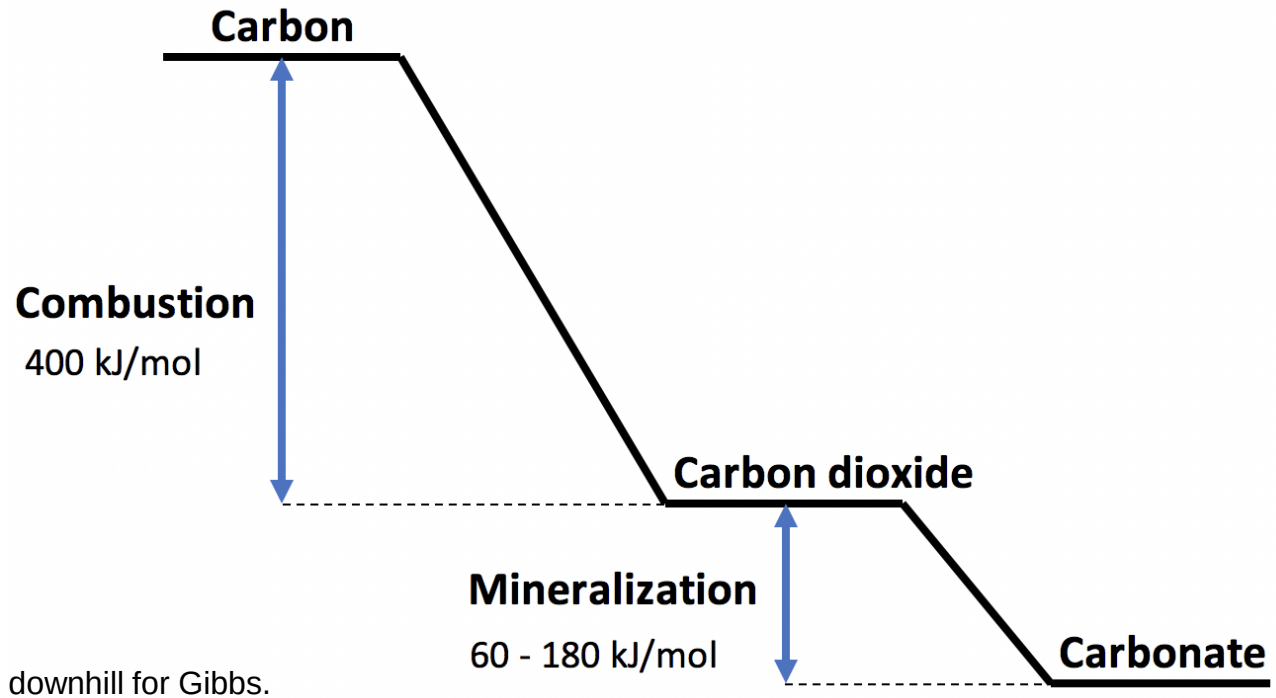
What do we do with 20,000,000,000 t CO_2 per year?

The success of any CO_2 capture depends on the storage.

What is carbon mineralization?

$$MO + CO_2 \rightleftarrows MCO_3 + heat$$

Safe, permanent, non-toxic, scalable method for CO_2 disposal.



Note: Heat of reaction shown – similar downhill for Gibbs.

Source: Lackner, Klaus S., et al. "Carbon dioxide disposal in carbonate minerals." *Energy* 20.11 (1995): 1153-1170. and Intergovernmental Panel on Climate Change, "Carbon Dioxide Capture and Storage," (2005).

Carbon mineralization: the resource scale

Mineral carbonates are the largest resource* for CO_2 sequestration.

***both in terms of storage capacity and storage time**

Exposed ultramafic rock formations

Globally: >10^5 Gt C storage capacity for >10^5 years

Basalt formations

Mine tailings

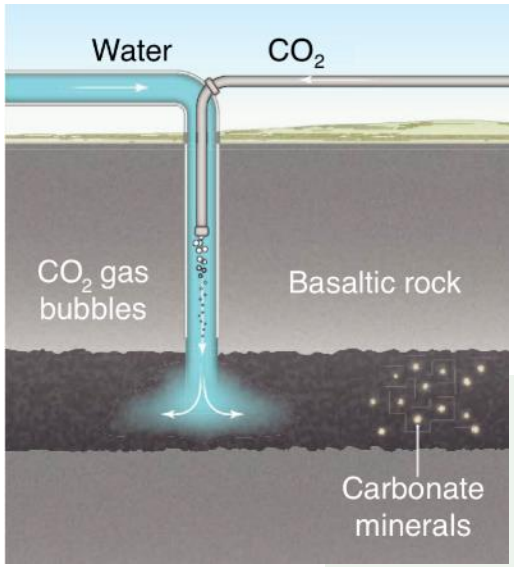
Source: Lackner, Klaus S., et al. (1995). and Lackner, Klaus S. "A guide to CO2 sequestration." *Science* 300.5626 (2003): 1677-1678.
Images adapted from: Krevor, S. C., et al. "Mapping the mineral resource base for mineral carbon-dioxide sequestration in the conterminous United States." US Geological Survey, 2009. and National Academies of Sciences, Engineering, and Medicine. "Negative emissions technologies and reliable sequestration: a research agenda." (2018).

Key factors in carbon mineralization

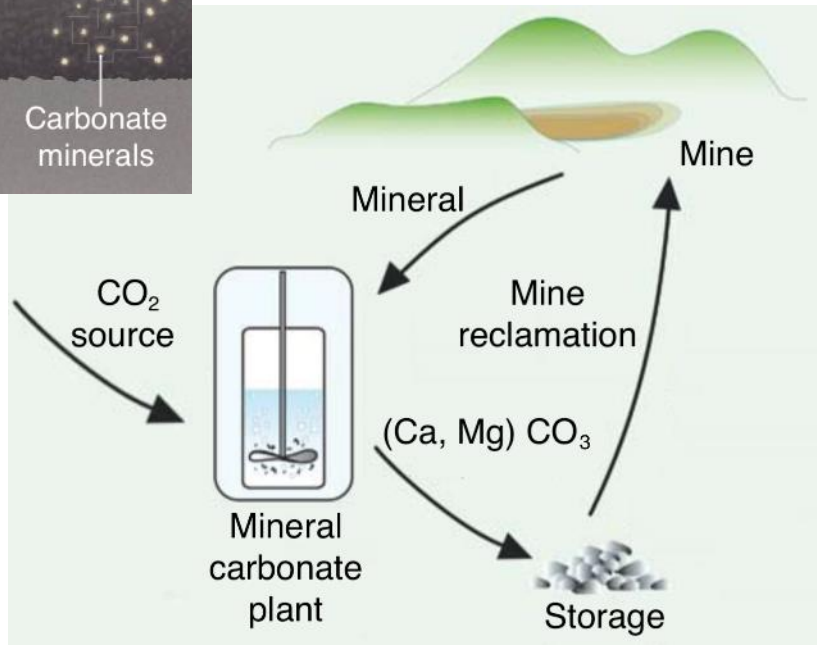
1. Carbonation **potential**: number of moles of CO_2 that can be converted
   - Inherent property of the rock

2. Carbonation **reactivity**: extent of reaction or conversion
   - Ties directly to capital expenditure
   - Sets the timescale (& therefore size)
   - Depends on mineral composition, pretreatment, solubility at time, temperature, and pressure, etc.

In situ

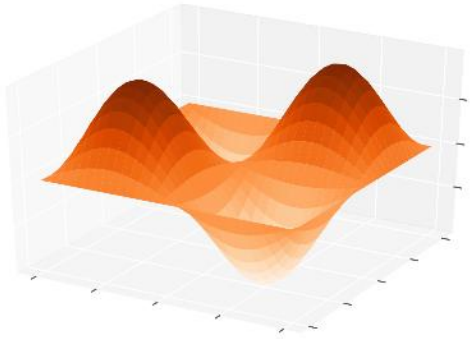


Ex situ



Source: O'Connor, W. K., et al. "Energy and economic considerations for ex-situ aqueous mineral carbonation." D0E/ARC-2004-028. US Department of Energy, Albany Research Center, Oregon, 2004.
Image (*in situ*) adapted from: www.greenoptimistic.com
Image (*ex situ*) adapted from: Intergovernmental Panel on Climate Change, "Carbon Dioxide Capture and Storage," (2005).

What's the catch?



High-grade energy requirement

Mapping the resource (for both *in situ* & *ex situ*)

Characterizing full-range of operating parameters

High CapEx

More research is needed to understand both fundamentals as well as opportunities for innovation.

Image (globe): VectorStock

Carbon mineralization kinetics

Challenge #1: process requires high-grade energy input.

Digging, crushing, grinding, and milling

Pre-treatment & other process steps, including varying temperature, pressure, pH, hydration, etc.

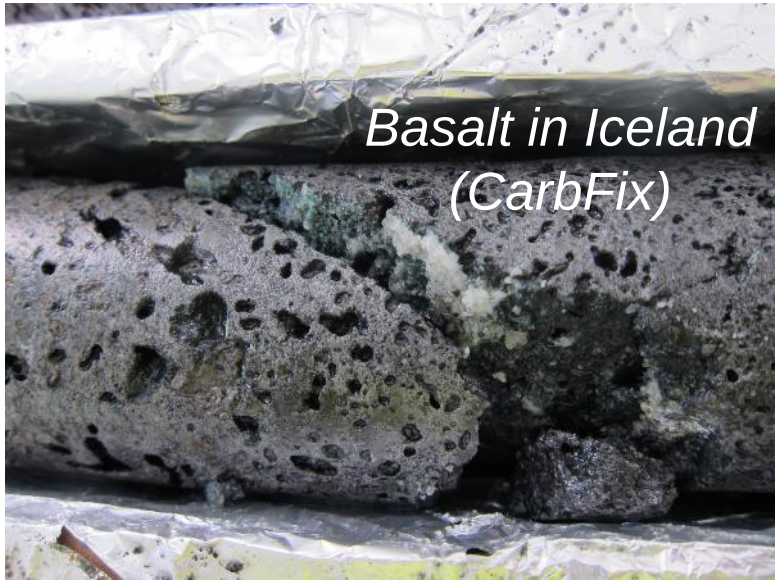
What are the most effective ways for accelerating the kinetics while decreasing the demand for high-grade energy?

Can we frac to accelerate the reaction process?

Image (grinding): http://machines.altervista.org/boost-efficiency-rock-grinder/
Image (litmus strips): www.amazon.com; Image (pressure gauge): www.surpluscenter.com; Image (thermometer): VectorStock

Mapping the resource (subject to the process)

Challenge #2: resource mapping & understanding subsurface conditions.



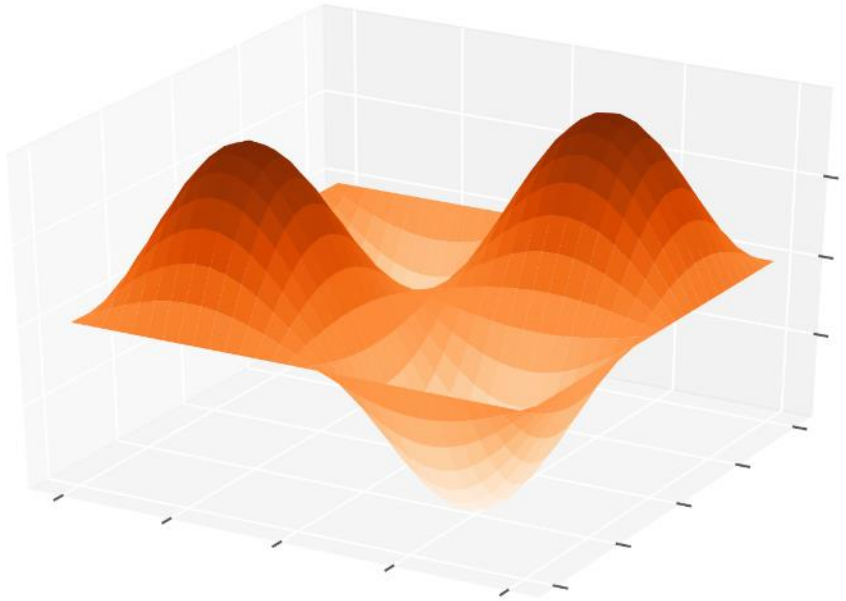
How do we best identify sites for both* in situ *and* ex situ *mineralization?

How do we characterize feedbacks between permeability, reactive surface area, and reaction rate?

Images (left to right): (1) Fountain, Henry. "How Oman's Rocks Could Help Save the Planet." *New York Times*. April 26, 2018., (2) Krevor, S. C., et al. *Mapping the mineral resource base for mineral carbon-dioxide sequestration in the conterminous United States*. US Geological Survey, 2009., (3) www.carbfix.com

Characterizing and understanding the full spectrum

Challenge #3: consistent and thorough characterization of multi-dimensional operating space.



A few items to explore:

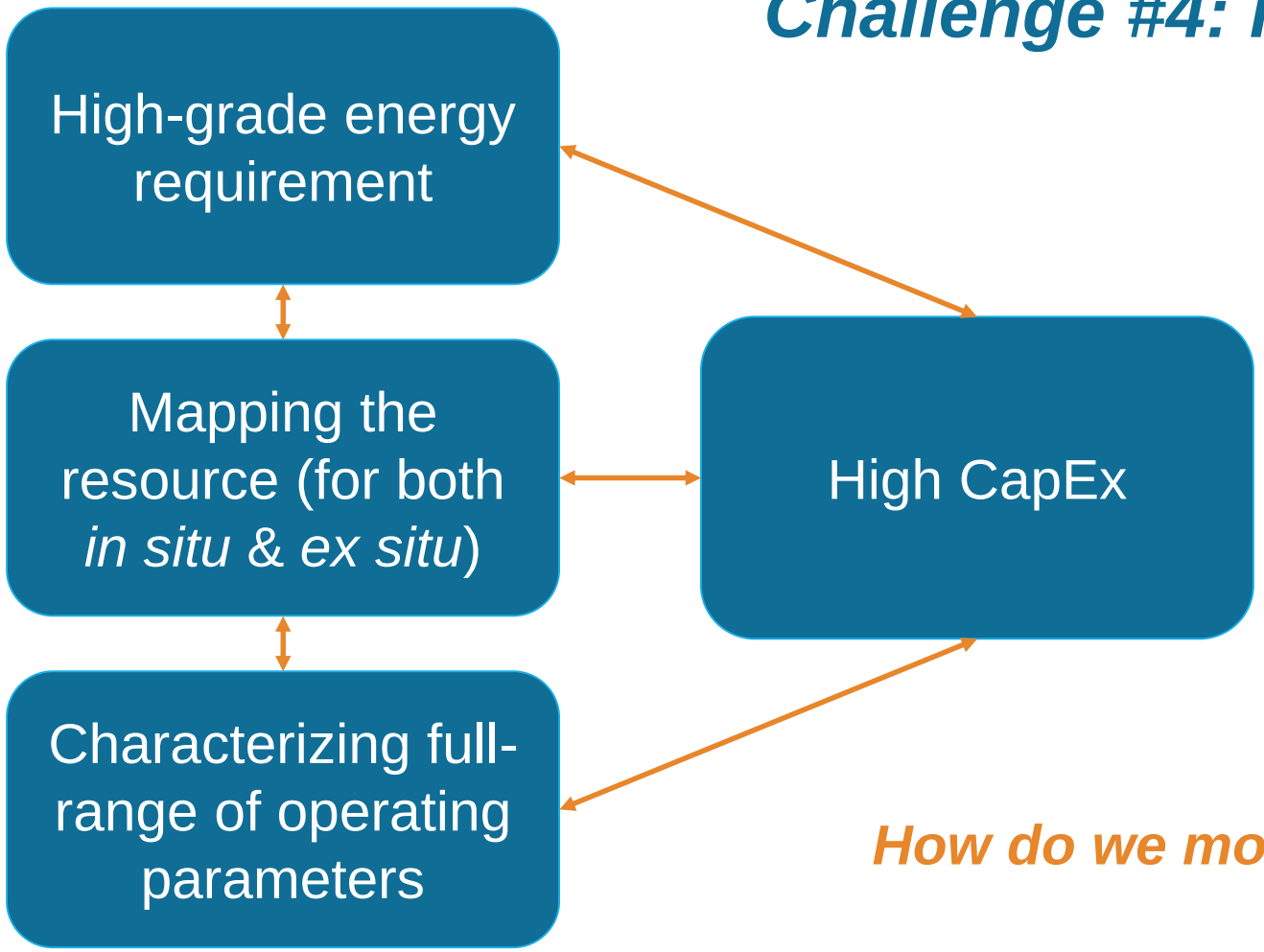
- **Consistency across experiments** to understand kinetics of different solid reactants with the same fluid composition
- Best ways to **deal with passivation**
- How to **use heat of reaction**
- How to best **verify *in situ* processes**

What are the best practices for consistent characterization?

Source: multiple papers by and conversations with Klaus S. Lackner, Peter Kelemen, and others.

We need to drive down the cost of carbon mineralization

Challenge #4: high capital expenditures.



CapEx is affected by the carbonation reactivity, including how intensive the reaction process is, the system kinetics, and the available resource.

How do we most effectively drive down the cost?

Negative emission technologies are vital.
Carbon mineralization warrants more attention.

Let's discuss.

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Coffee with ARPA-E: Wednesday, 8 am